Heat mitigation
through landscape and urban design

Using observations and microclimate modeling
to find the best strategy

SCN Green Infrastructure (GI) Workgroup Meeting
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Welcome to the desert!

- **mild winters**

  average high temperatures between 66 °F and 71 °F from December to February

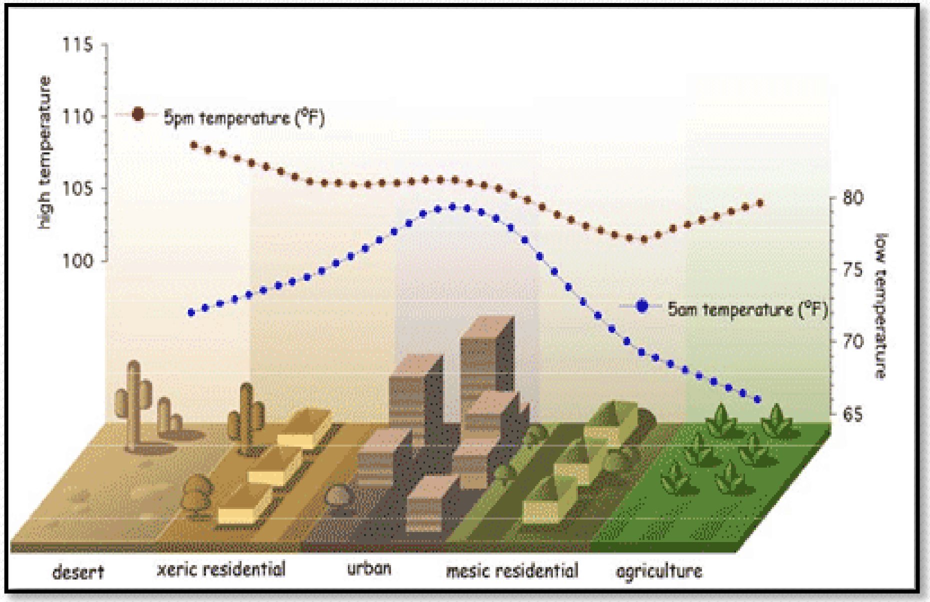
- **hot summers**

  average high temperatures over 100 °F from June - August

annual average rainfall of 8 inches

It's a dry heat, they said!

- **In the summer: high temperatures and increased solar intensity during the day, Urban Heat Island (UHI) at night**
- **Impacts**
  - human health (increased heat stress, more heat-related illnesses/deaths)
  - human comfort
  - energy consumption for A/C use
  - water use for irrigation
  - air quality

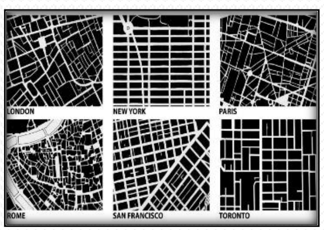


credit: censam.mit.edu

Examples for heat mitigation strategies

- **Urban Forest**
  - ✚ Cools through shading and evapotranspiration
  - – water use concerns in desert environments

- **Urban fabric modification**
  - ✚ high surface albedo increases reflectivity and reduces heat absorption
  - – research suggests albedo modification impacts precipitation



- **Urban form modification**
  - density and height-to-width ratio of buildings alters ventilation and wind patterns

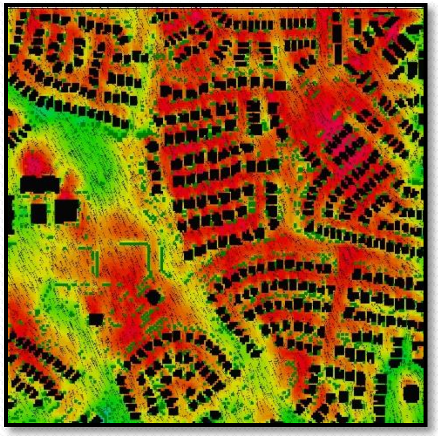
What is the site-specific impact of these strategies? How effective are they?

Why Modeling?

- **Knowledge about urban climate is important for designing sustainable cities, but there is no test bed**

- **What if?!**

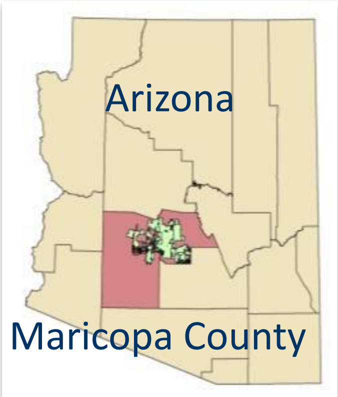
- **Models can help us**
  - understand present climate and what factors create a particular climate
  - project climatic conditions into the future
  - run experiments and create scenarios

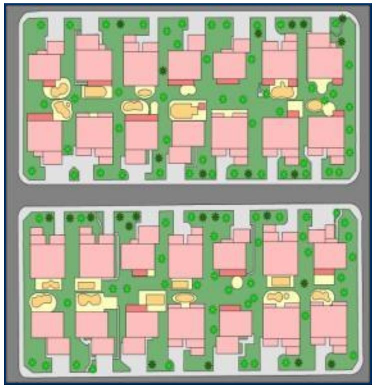


- **Meteorological observations**
  - also help us understand present climate and what factors create a particular climate
  - important for climate model validation

Scales in climate modeling

global → **regional** → **local** → **micro**





IPCC's GCMs | **WRF model** | **LUMPS model** | **ENVI-met model**

scales at which most UHI mitigation strategies are implemented and the effect will be felt most

Phoenix heat mitigation studies

1 Urban Form Project

- How does urban form, design, and landscaping affect mid-afternoon summer microclimate in Phoenix neighborhoods?

2 Cool Urban Spaces Project

- What are the cooling benefits achieved by
  - increasing the tree canopy from 10% (current) to 25% (2030 goal)
  - implementing cool roofs

  for a typical residential neighborhood in the City of Phoenix under existing conditions and projected warming during pre-monsoon summer?

3 North Desert Village Tree and Shade Project

- What is the diurnal thermal benefit of tree shade?

Phoenix heat mitigation studies

1 Urban Form Project

- How does urban form, design, and landscaping affect mid-afternoon summer microclimate in Phoenix neighborhoods?

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ELSEVIER

Research Paper

Impact of urban form and design on mid-afternoon microclimate in Phoenix Local Climate Zones☆

CrossMark

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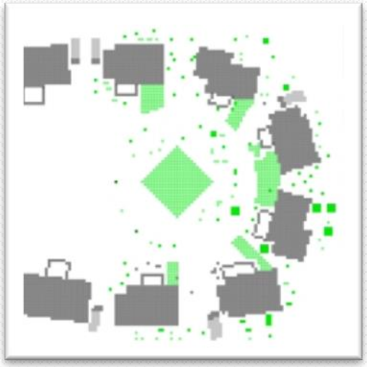
HIGHLIGHTS

- Cooling is not only a function of vegetation and surface materials, but also dependent on the form and spatial arrangement of urban features.
- At the microscale, urban form has a larger impact on daytime temperatures than landscaping.
- In mid-afternoon, dense urban forms can create local cool islands.
- Spatial differences in cooling are strongly related to solar radiation and local shading patterns.
- The LCZ classification scheme is a useful concept for integrating local climate knowledge into urban planning and design practices.

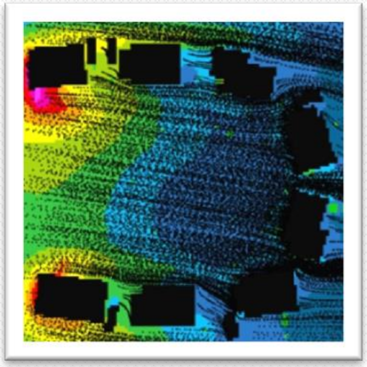
Middel, A., Häb, K., Brazel, A.J., Martin, C., Guhathakurta, S., 2014. Impact of urban form and design on microclimate in Phoenix, AZ. *Landscape and Urban Planning* **122**, 16–28.

ENVI-met model

- **3D Computational Fluid Dynamics model**
  - developed by Michael Bruse & team, University of Mainz, Germany



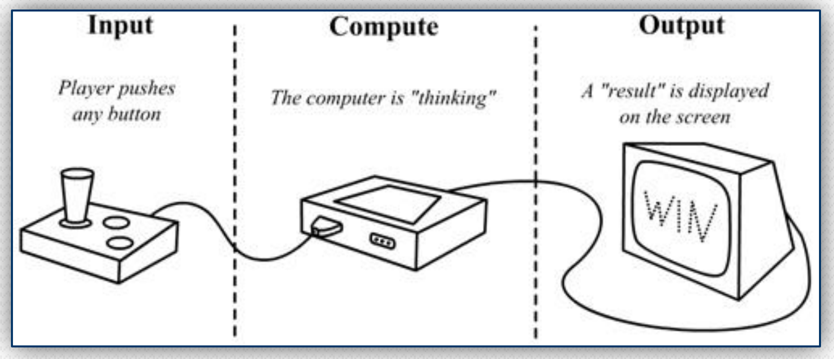
- **Model inputs**
  - plant database
  - physical soil structure and profile
  - area input file
    (arrangement of built structures and vegetation)
  - configuration file
    (meteorological data and simulation parameters)



- **Model output**
  - 3D microclimate

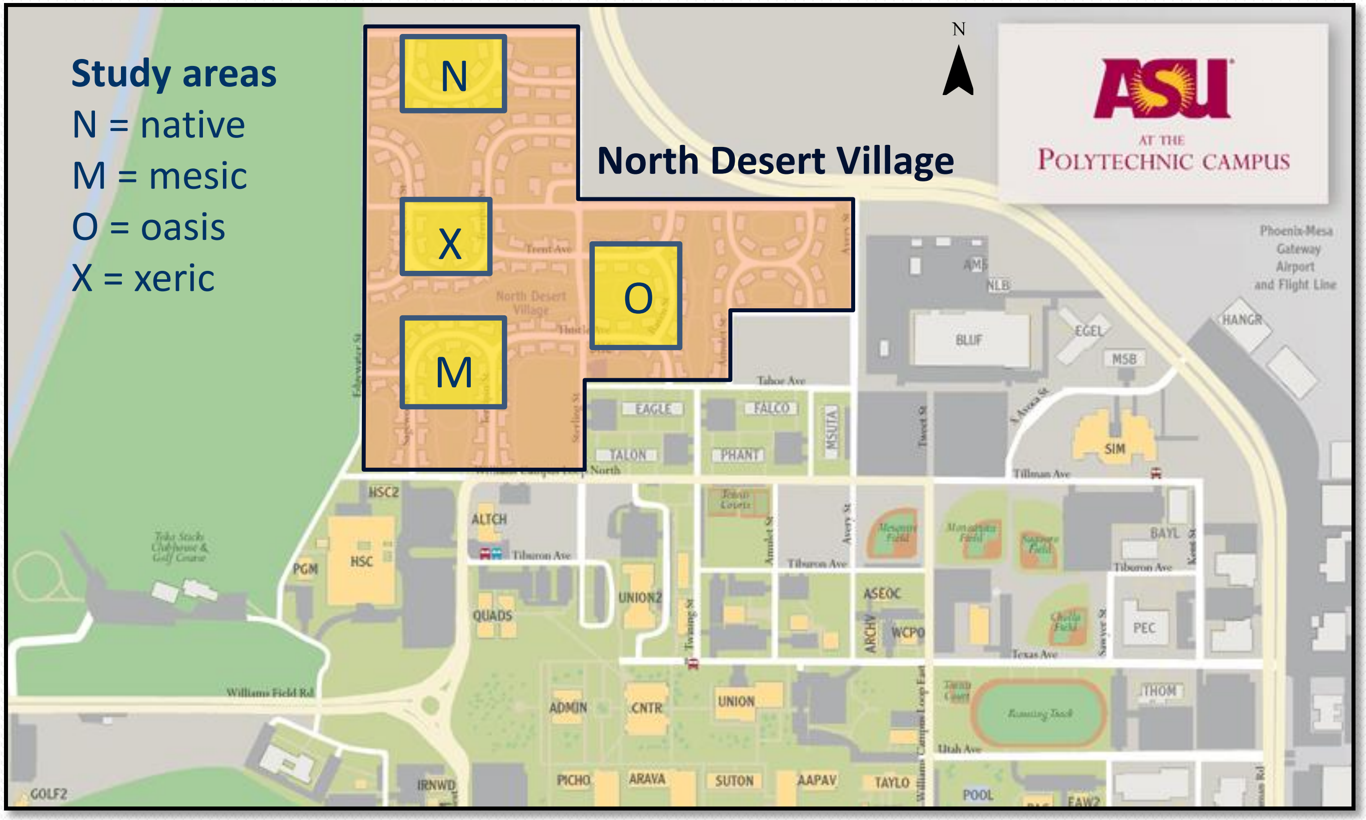
Methodology

- **ENVI-met model validation**
  - using meteorological observations from existing neighborhoods in Phoenix
  - typical Phoenix pre-monsoon summer day (June 23, 2011)
- **Development of urban form scenarios**
  - using "*Local Climate Zones*" classification after Stewart and Oke (2012)
- **ENVI-met simulations**
  - combining urban form scenarios with 3 landscaping types
  - ensemble of 13 scenarios



Stewart, I. D., Oke, T. R., 2012. Local climate zones for urban temperatures studies, *Bulletin of the American Meteorological Society* **93**(12), 1879-1900.

North Desert Village (NDV) location



NDV neighborhoods

mesic

native

oasis

xeric

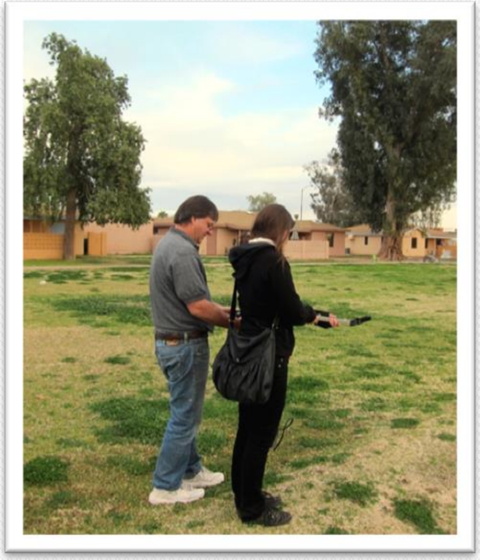
Data acquisition (I)

meteorological station in the center of each neighborhood

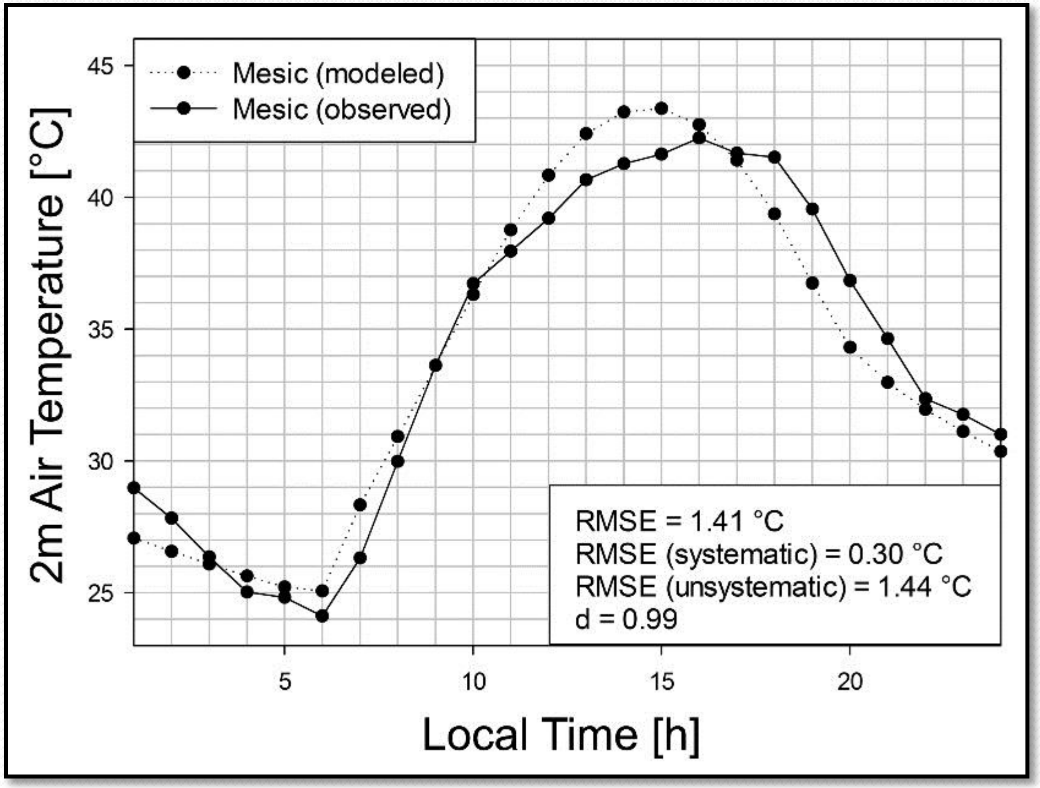
Data acquisition (II)

Creating an inventory of trees and shrubs

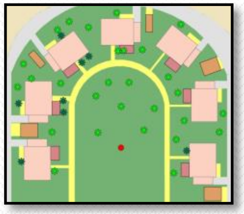
Leaf Area Index (LAI) measurements
using the Li-Cor LAI-2000 Plant Canopy Analyzer



Model validation (example)

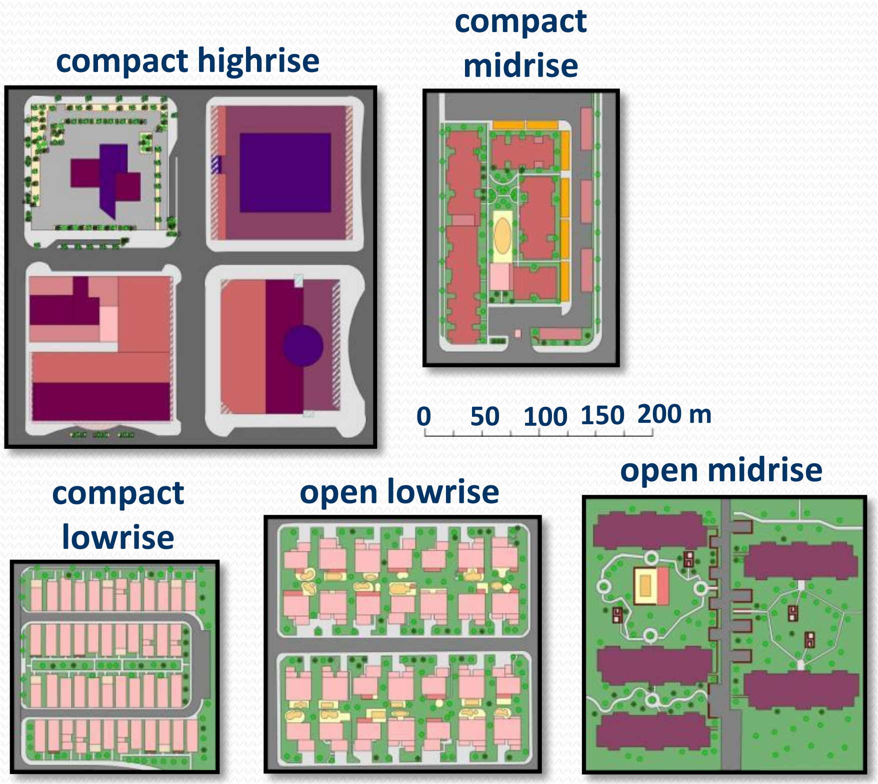


mesic



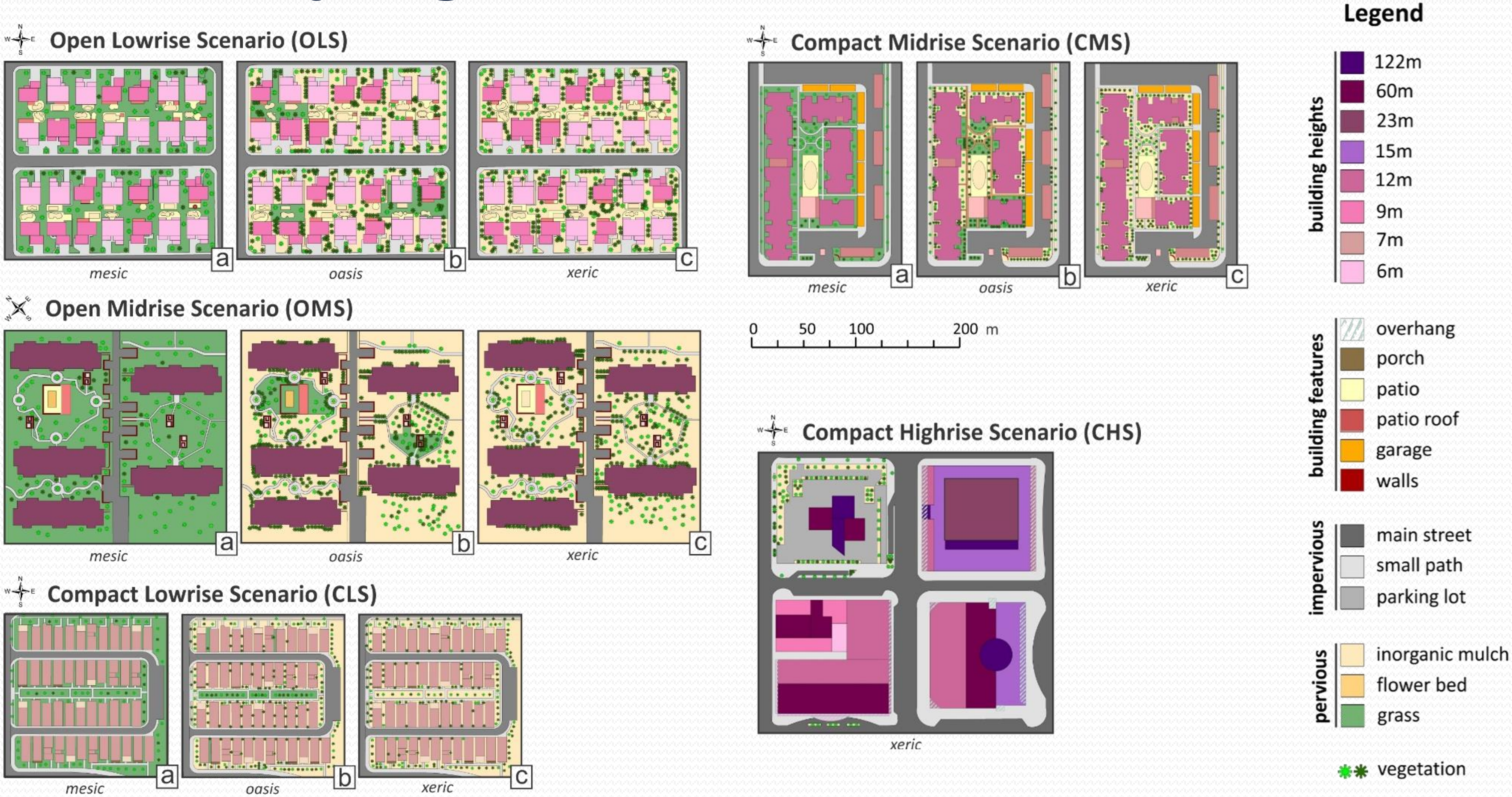
Local Climate Zones (LCZs)

- **Research framework for urban heat island studies**
- **Classification system to standardize the worldwide exchange of urban temperature observations**
- **17 zone types at the local scale (10^2 to 10^4 m)**
- **Each LCZ is unique in its combination of surface structure, cover, and human activity**

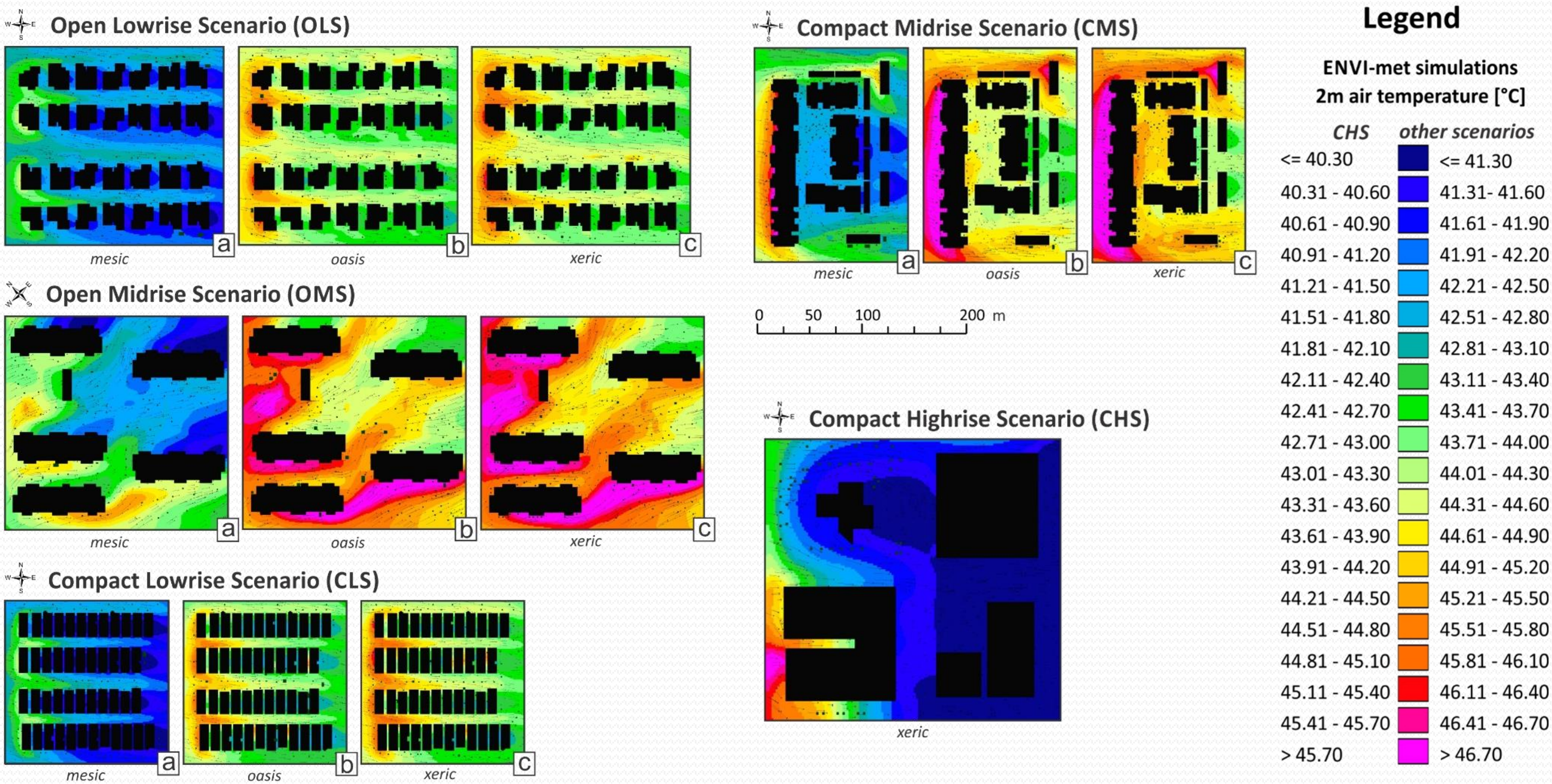


Stewart, I. D., Oke, T. R., 2012, Local climate zones for urban temperatures studies, *Bulletin of the American Meteorological Society*, **93**(12), 1879-1900.

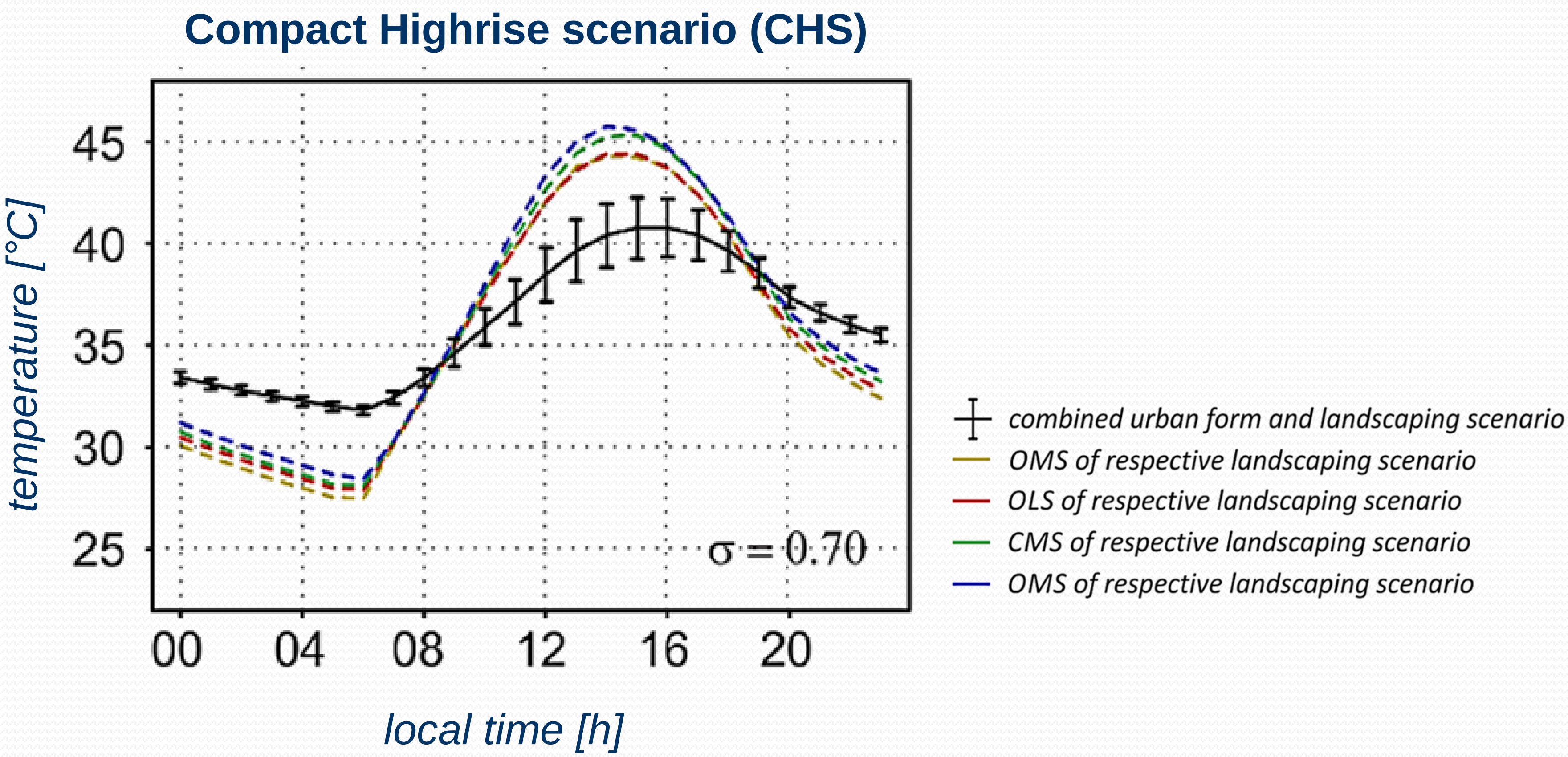
Landscaping scenarios



2m air temperature at 3PM (June 23, 2011)



Diurnal 2m air temperature, xeric



Key findings

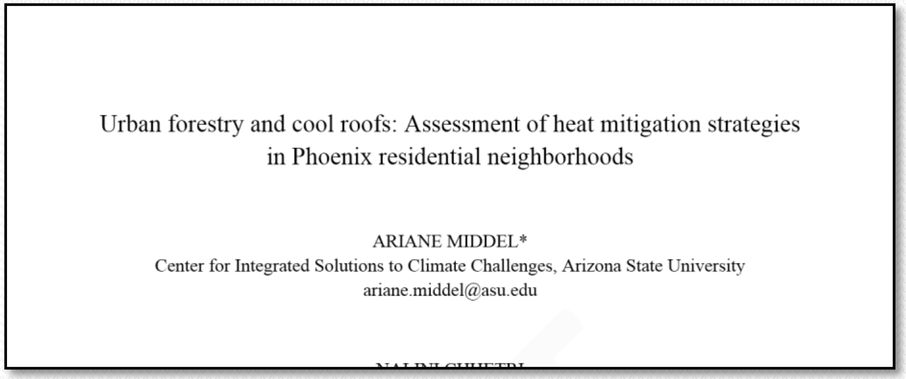
- Cooling is not only a function of *vegetation* and *surface materials*, but also dependent on the *form and spatial arrangement* of urban features
- In mid-afternoon, dense urban forms can create *local cool islands*
  - spatial differences in cooling are strongly related to solar radiation and local shading
  - compact scenarios were most advantageous for daytime cooling
  - urban canyon effects produced by arrangement of mid- to high- rise buildings along the direction of wind flow help in reducing daytime temperatures
- *advection* is important for the distribution of within-urban-design temperatures

Phoenix heat mitigation studies

2 Cool Urban Spaces Project

- What are the cooling benefits achieved by
  - increasing the tree canopy from 10% (current) to 25% (2030 goal)
  - implementing cool roofs

  for a typical residential neighborhood in the City of Phoenix under existing conditions and projected warming during pre-monsoon summer?



Urban forestry and cool roofs: Assessment of heat mitigation strategies in Phoenix residential neighborhoods

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Middel et al., Urban forestry and cool roofs: Assessment of heat mitigation strategies in Phoenix residential neighborhoods. *Urban Forestry and Urban Greening*, manuscript in preparation.

Project goal

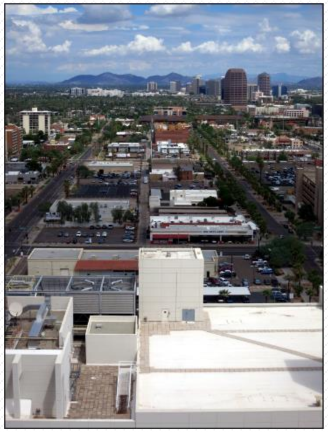
- **Quantify the thermal impact of two heat mitigation activities currently undertaken by the City of Phoenix**

- **Phoenix Tree and Shade Master Plan (2010)**

  urban Forestry initiative to incrementally achieve a tree canopy cover goal of 25% by 2030 for the entire city

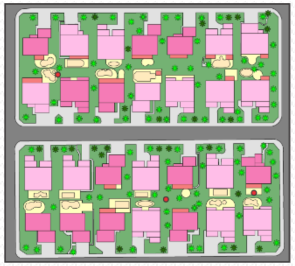
- **Cool Roof initiative**

  coat 70,000 square feet of the city's existing rooftops with reflective paint



Methodology

- **ENVI-met modeling**
  - simulate an ensemble of tree canopy cover, cool roof, and climate scenarios for a residential neighborhood in Phoenix
  - typical summer day (June 23, 2011)
    - minimum temperatures of 79 °F (26 °C)
    - maximum temperatures of 109 °F (43 °C)
    - no precipitation
    - no cloud cover
- **Analysis of average neighborhood 2m air temperature at 3PM**



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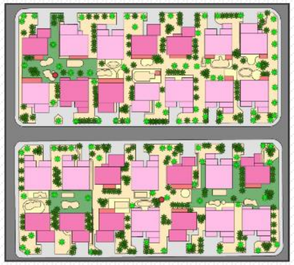
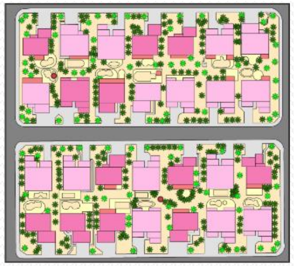


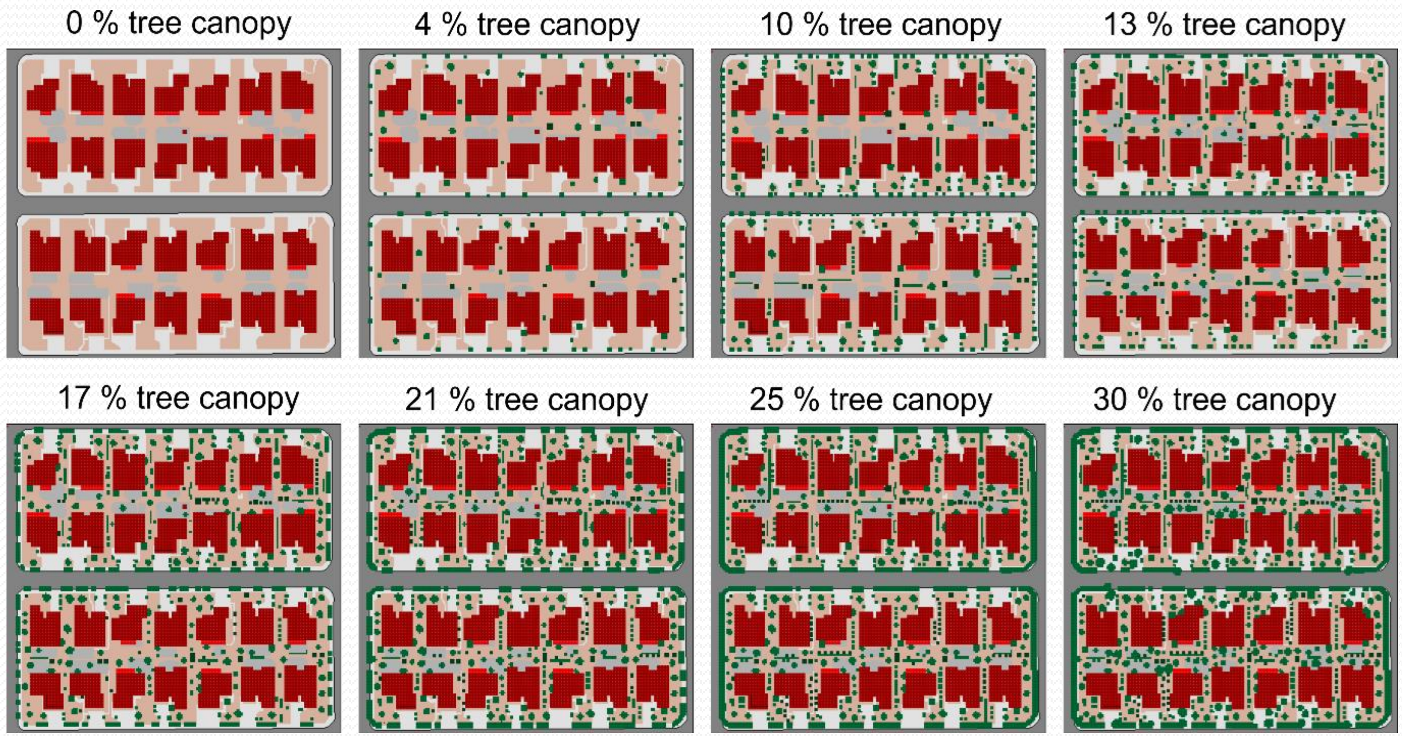
oasis



xeric

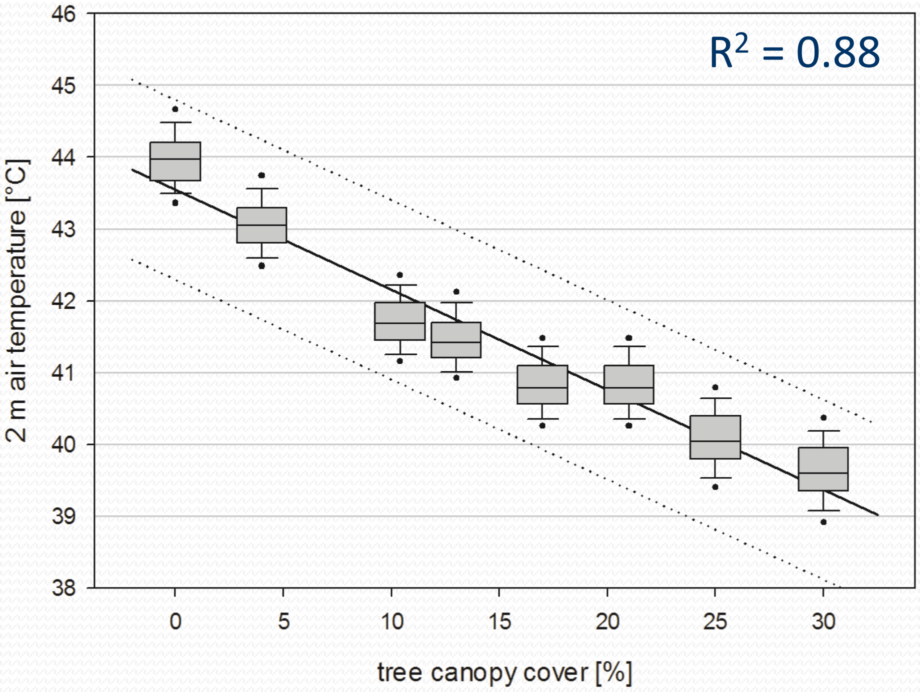
Step 1: Relationship between tree canopy cover and air temperature

xeric residential neighborhood, current summer conditions, regular roofs



Tree canopy cover vs. air temperature

averaged neighborhood 2m air temperatures
modeled by ENVI-met for June 23, 2011, 3PM

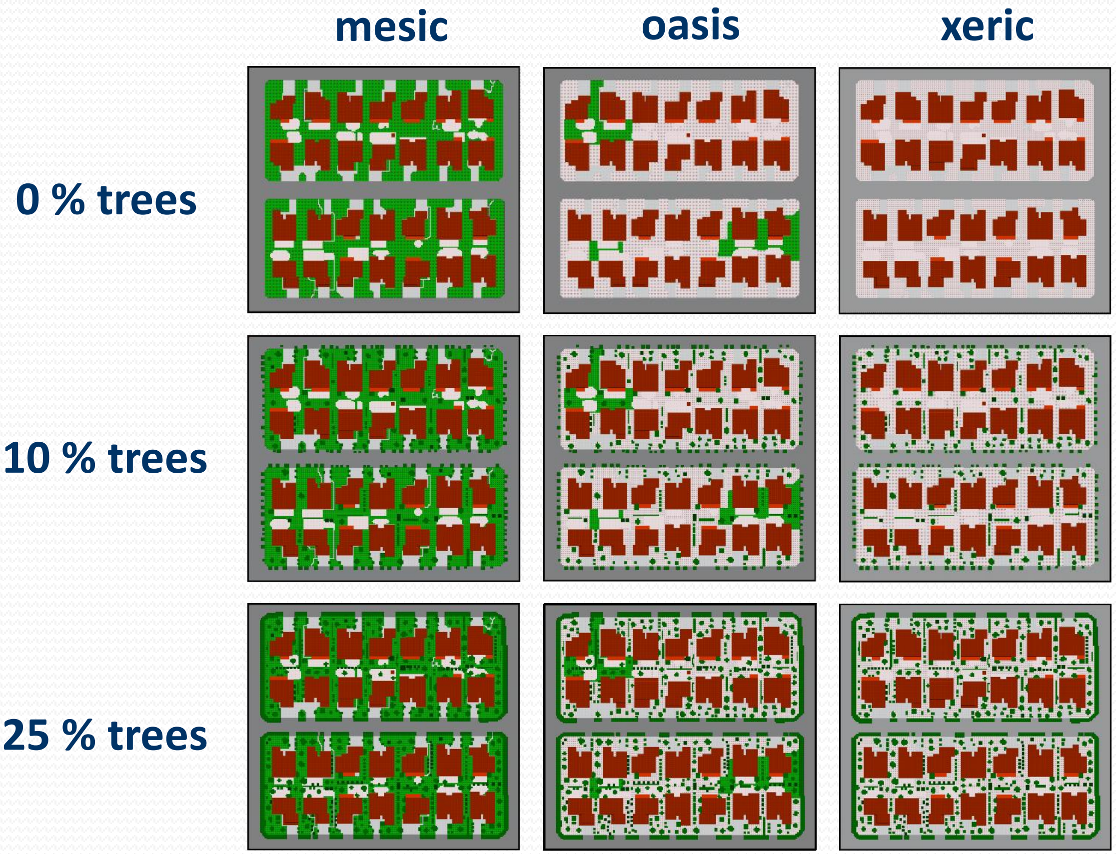


Linear relationship with 0.14 °C cooling per percent increase in tree cover, assuming the same urban form

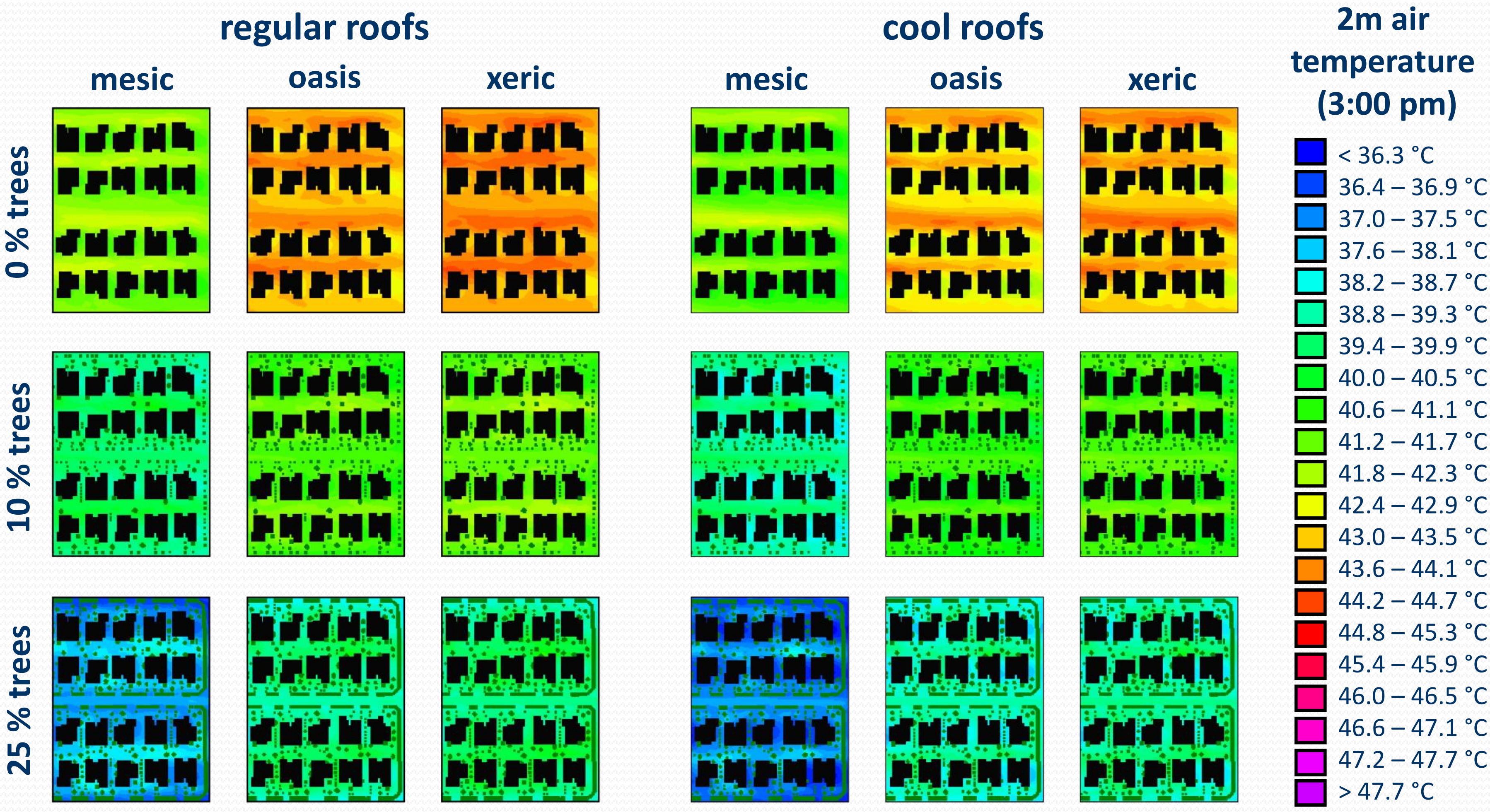
Step 2: 54 Tree-roof-climate scenarios

	regular roofs			cool roofs		
	0% tree canopy	10% tree canopy	25% tree canopy	0% tree canopy	10% tree canopy	25% tree canopy
current summer conditions	M O X	M O X	M O X	M O X	M O X	M O X
climate scenario 1 (+ 1 °C)	M O X	M O X	M O X	M O X	M O X	M O X
climate scenario 2 (+ 3 °C)	M O X	M O X	M O X	M O X	M O X	M O X

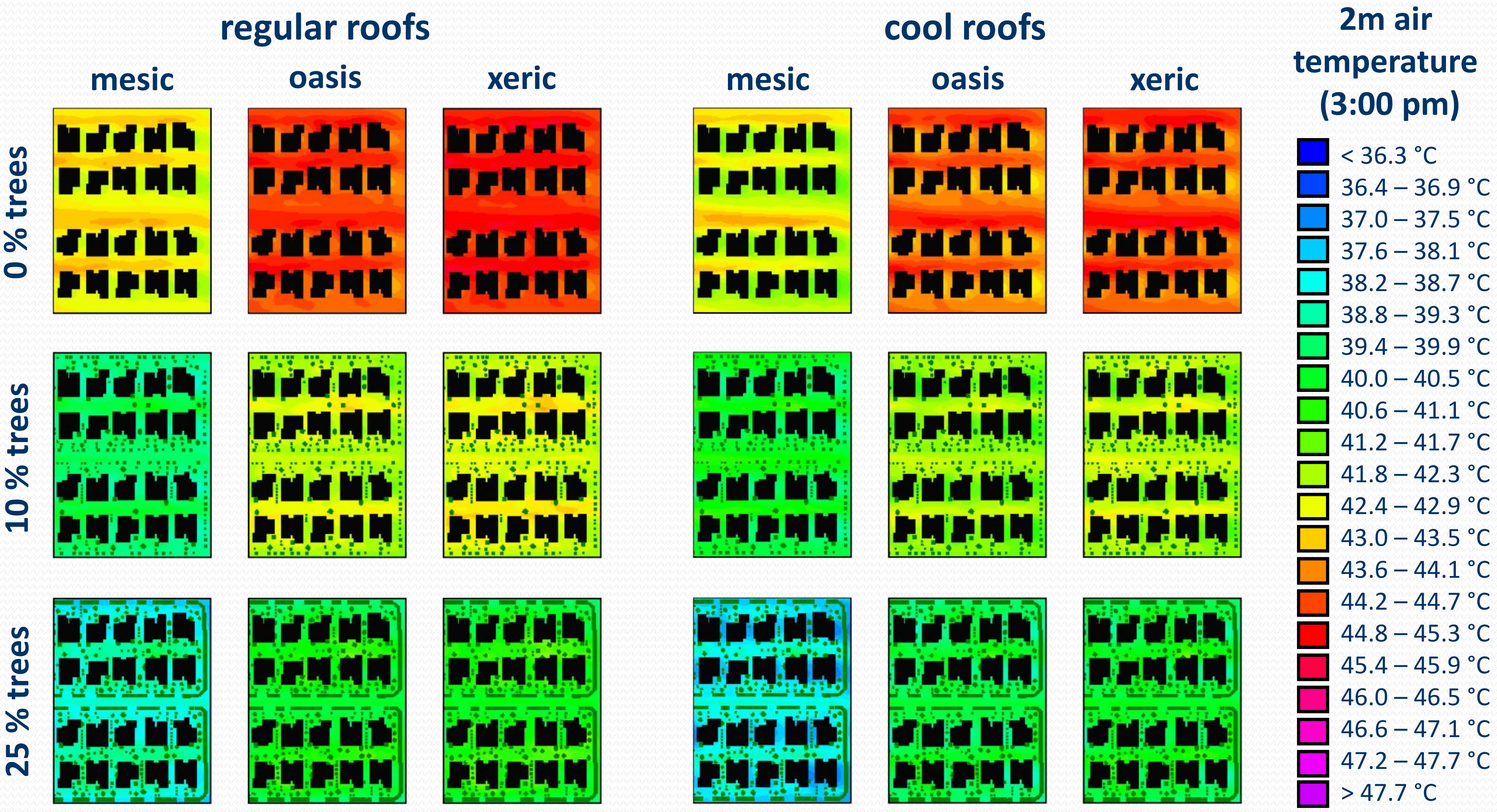
Combined tree and landscaping scenarios



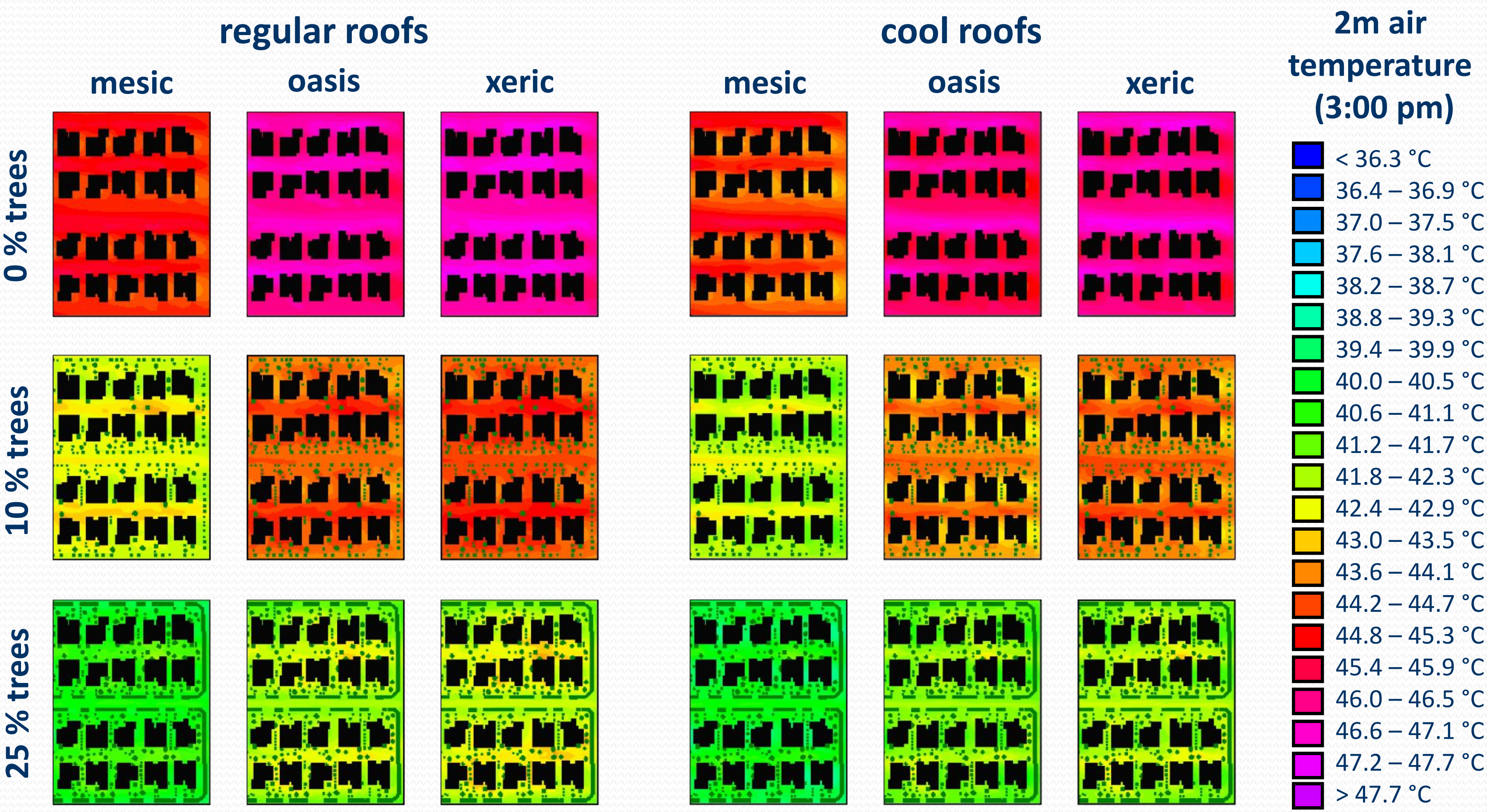
Current Climate



Climate Change + 1 °C

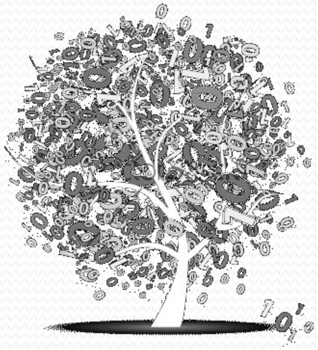


Climate Change + 3 °C



Key findings

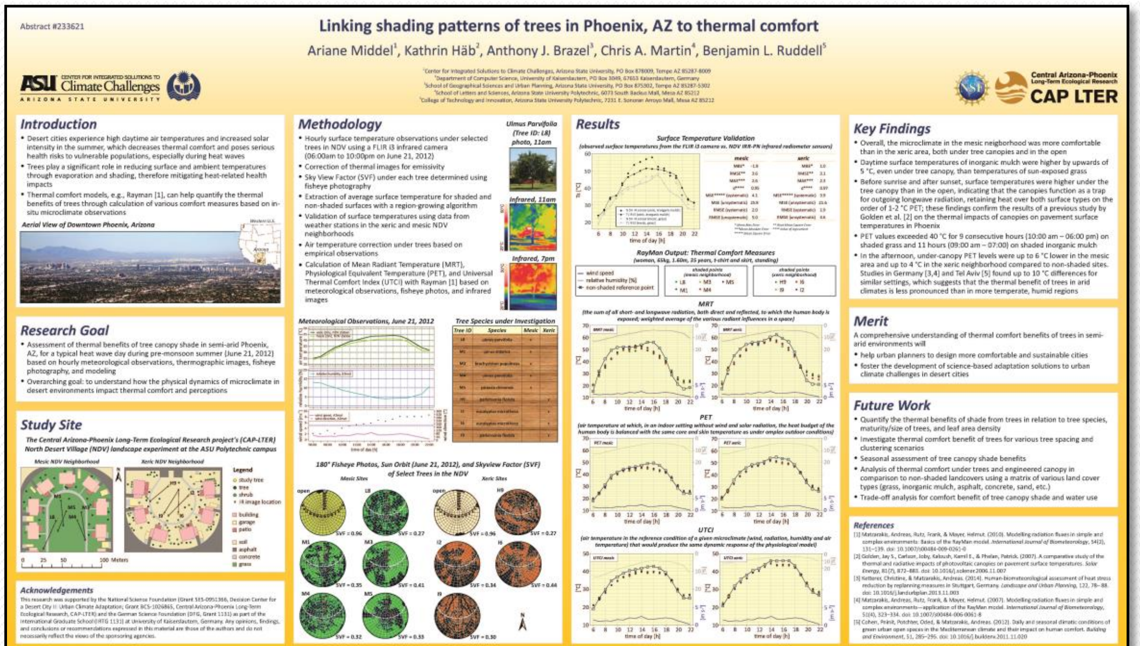
- **An increase in tree canopy cover yields 0.14 °C cooling per percent increase, assuming the same urban form**
- **The relationship between canopy cover and cooling becomes less clear when examined in combination with varying neighborhood designs**
  - grass and other vegetative cover have an impact on air temperature
  - modifications of land surface cover changes the heat storage capacity
  - urban form affects microclimate through a change in wind patterns and shading
  - the arrangement and type of trees have an impact on the cooling benefit
- **At the neighborhood scale**
  - cool roofs provide a daytime cooling benefit of 0.3 °C (0.5 °F)
  - an increase in tree canopy cover from 10% to 25% trees will result in daytime cooling benefits of up to 2 °C (3.6 °F)



Phoenix heat mitigation studies

3 North Desert Village Tree and Shade Project

- What is the diurnal thermal benefit of tree shade?



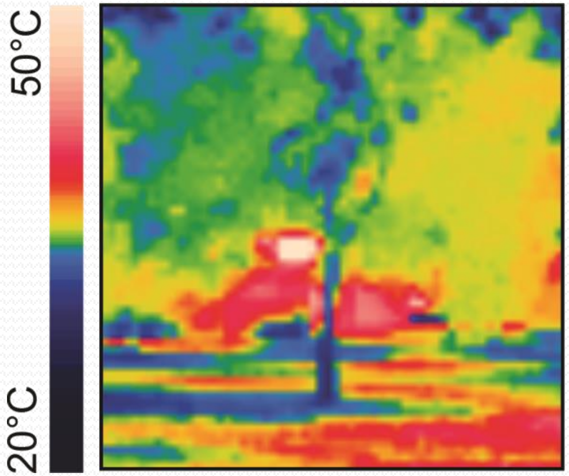
Middel, A., K. Häb, A. J. Brazel, C. A. Martin and B. L. Ruddell. 2014. Linking shading patterns of trees in Phoenix, AZ, to thermal comfort. Poster presented at the 11th Symposium on the Urban Environment, American Meteorological Society 94th Annual Meeting, February 2-6, 2014, Atlanta, GA.

Methodology

- **Hourly surface temperature observations under selected trees in NDV using a FLIR i3 infrared camera**
  - 6 AM to 10 PM on June 21, 2012
  - meteorological data from NDV weather stations
  - fisheye photography of the tree canopy
- **Extraction of average surface temperature for shaded and non-shaded surfaces**
- **Thermal comfort modeling with Rayman**
  - model calculates atmospheric conditions and human thermal comfort in urban areas based on meteorological observations and fisheye photos

Chinese Elm, mesic neighborhood (NDV)

11:00 AM | **11:00 AM** | **07:00 PM**



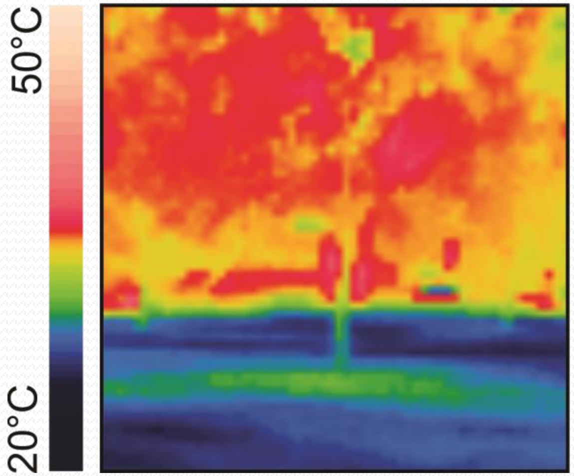


photo | **thermographic images**

Fisheye photos

mesic

open

ulmus parvifolia

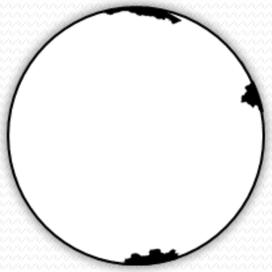
pinus eldarica

brachychiton populneus

ulmus parvifolia

pistacia chinensis

xeric



open

parkinsonia florida

eucalyptus microtheca

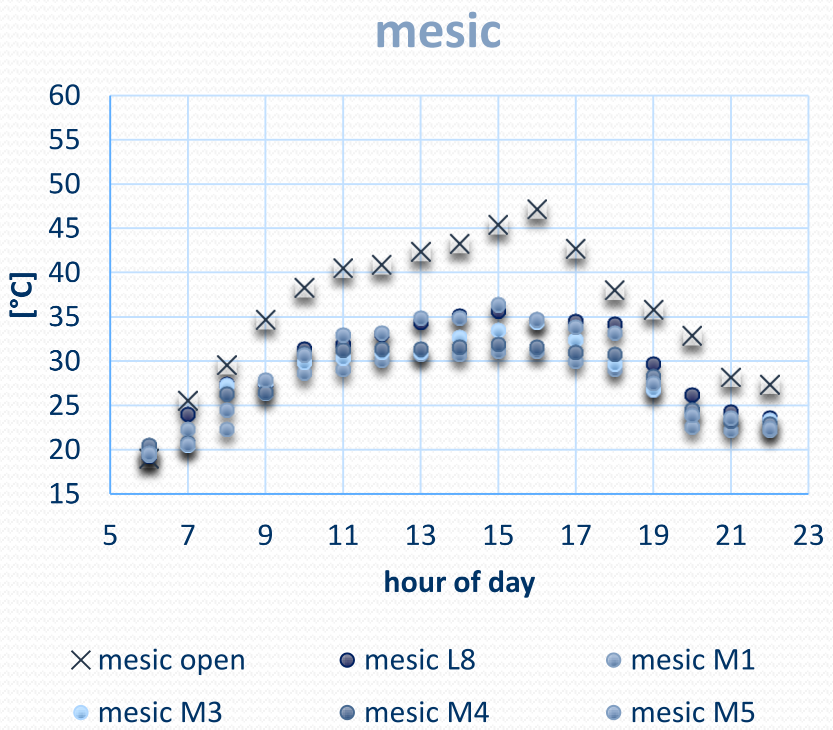
eucalyptus microtheca

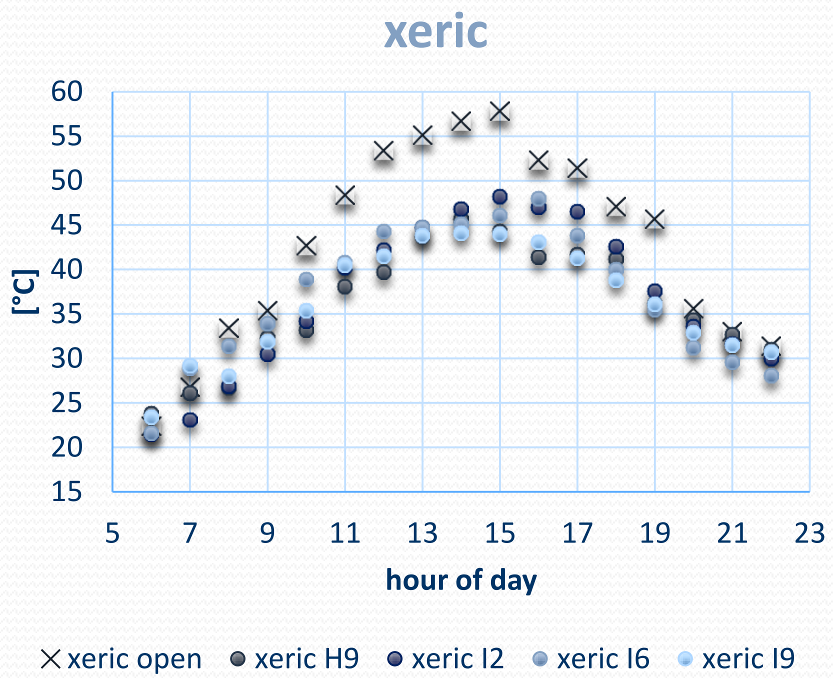
parkinsonia florida

→ Rayman

Observations for June 21, 2012

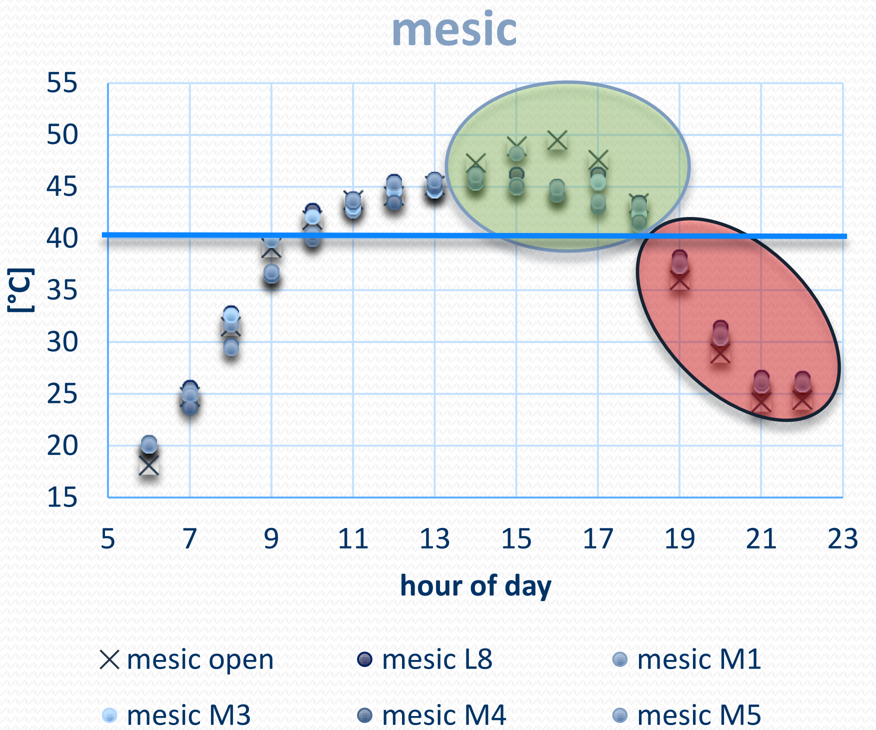
surface temperatures, shaded (x) vs. non-shaded (·)

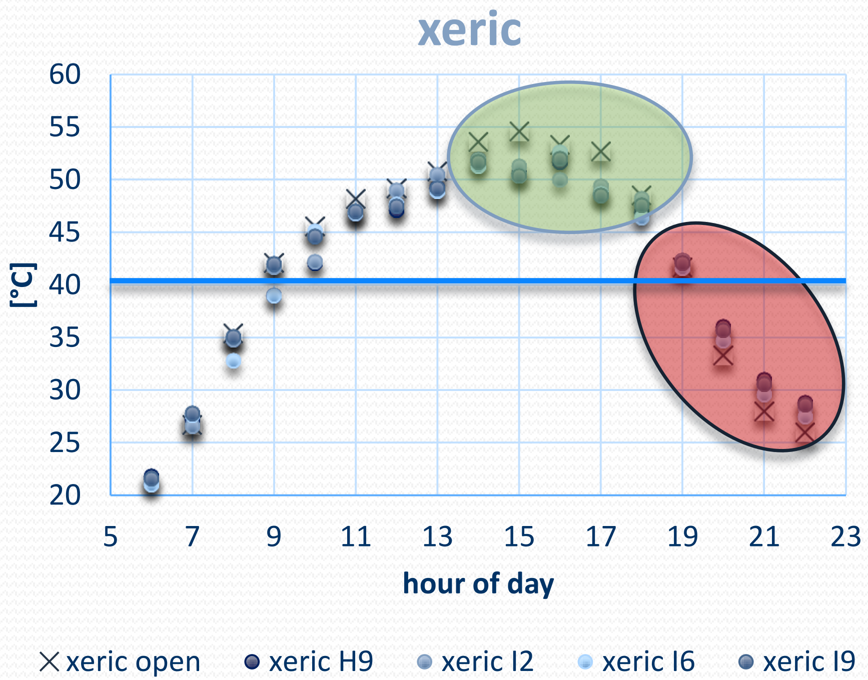




Thermal comfort (modeled with Rayman)

PET (Physiologically Equivalent Temperature)
for a woman (65 kg; 1.60 m; 35 years; t-shirt and skirt)





Key findings

- **PET values exceeded 40 °C for 9 consecutive hours (10 AM – 6 PM) on shaded grass and 11 hours (9AM – 7PM) on shaded gravel**

- **Tree shade increased thermal comfort by up to 5 °C PET in the afternoon**
  - locally, even a single tree can increase thermal comfort during the day, but the effect is also dependent on the surrounding urban design
- **Before sunrise and after sunset, surface temperatures were higher under the tree canopy than in the open**
  - canopies function as a trap for outgoing longwave radiation, retaining heat over both surface types on the order of 1-2 °C PET

Future work on heat mitigation

- **Urban form and design**
  - investigate impact of urban form and design on nighttime temperatures
  - analyze microclimate variability at various upwind speeds, times of day and year for different land cover compositions and patch sizes
- **Urban forestry**
  - quantify the thermal benefits of tree shade in relation to tree species, maturity/size of trees, leaf area density, tree spacing and clustering
  - seasonal assessments of tree canopy shade benefits
  - analysis of thermal comfort under trees and engineered canopy using a matrix of various land cover types (grass, inorganic mulch, asphalt, concrete, etc.)
  - trade-off between water use and thermal comfort

Conclusions

- **Understanding the dynamics of microclimate is important for the design of sustainable cities**
- **Modeling and observations can help us**
  - understand present climate and what factors create a particular climate
  - assess landscape and urban design strategies for heat mitigation

Thank you!

Questions?